Role and objectives of control for wind turbines

Extrée p. 135 - 140

F0307/02D

W.E. Leithead, PhD
S. de la Salle, BSc
D. Reardon, BEng

XP 000219783

8049c IEE Proceedings-C
138(1991)March,No.2,Part C,Stevenage,Herts.,GB

Indexing terms: Wind power, Torque, Control systems

Abstract: Variable pitch is used in many wind turbines to regulate power generation. The choice of control objectives is broadly examined together with the influence of the controller on the dynamics of the wind turbine.

1 Introduction

It is the purpose of the paper to investigate and clarify the role of the control system of a wind turbine. A complete review of the control and modelling of wind turbines has been given by Leithead [1].

There are two basic configurations of wind turbines, the horizontal axis wind turbine depicted in Fig. 1*a* and the vertical axis wind turbine depicted in Fig. 1*b*. Control issues are relevant only to the former, and the wind turbines discussed in this paper are of that type. The major components of the turbine are the tower, rotor (the blades and hub) and power train (the drive train and power generation unit). The drive train consists of the low-speed shaft, gearbox and coupling, if any, and high-speed shaft as shown in Fig. 2. The wind turbine configuration is assumed to conform to the following specification

(i) horizontal axis
(ii) grid connected
(iii) medium/large scale
(iv) variable pitch capability
(v) all blades acting in unison
(vi) generated power measurement.

There are no further restrictions. The turbine may be constant speed with or without compliance adding devices in the drive train or variable speed with all possible speed ranges. It is assumed that the variable pitch capability is employed in a regulating fashion, with all blades acting in unison, and the operational usage which best exploits it (and cost/efficiency implications) is investigated.

To have each blade acting independently requires independent instrumentation and actuation for each blade plus co-ordination of regulation at a higher level. The extra cost involved is generally assessed by the industry to outweigh any benefits [2, 3]. There is in principle, however, no difficulty in providing independent control of each blade, and this might be incorporated in

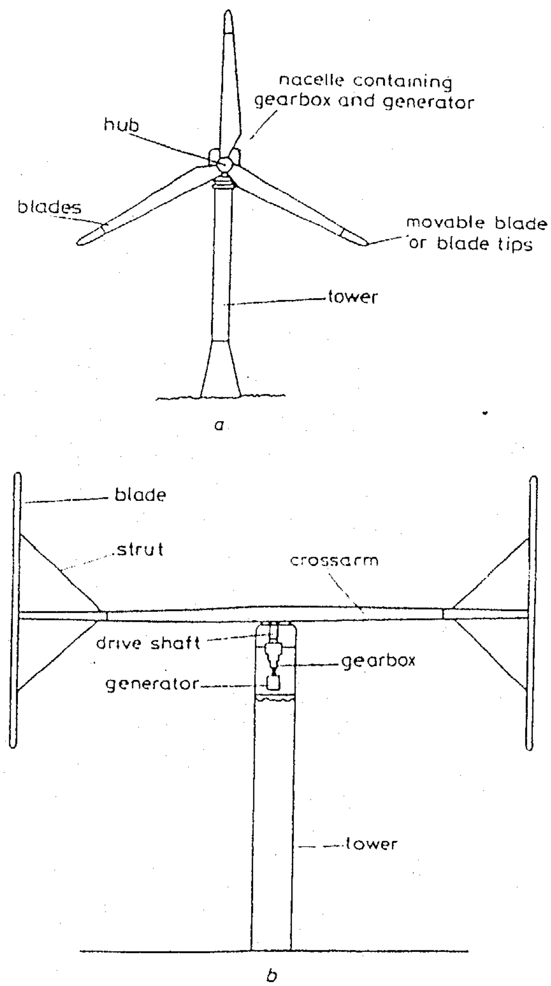

Fig. 1 *Wind turbine configurations*
a Horizontal axis wind turbine
b Vertical axis wind turbine

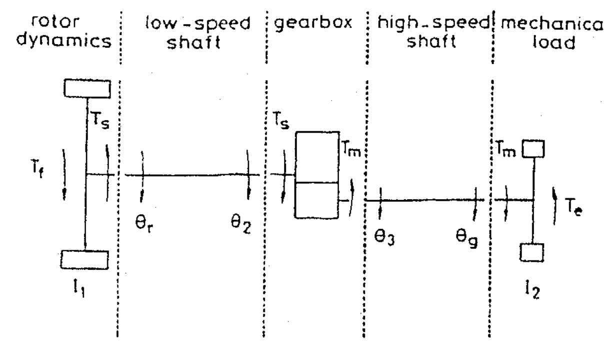

Fig. 2 *Schematic form of physical model for drive train*

Paper 7783C (P10, P11), first received 16th May and in revised form 17th September 1990

The authors are with the Industrial Control Unit, University of Strathclyde, Marland House, 50 George Street, Glasgow G1 1QE, United Kingdom

However, power fluctuations are not the most important consequence of the variation of loads. This variable load environment contributes [illegible]tly to the fatigue of the turbine components. To guarantee an acceptable fatigue life the components are specified to withstand loads greater than those required by the nominal rating of the turbine. Variations in loads cannot be completely eliminated but reducing their magnitude is desirable. The load capacity of the components can be set closer to the turbine rating without sacrificing fatigue life; increased power production is possible, or, equivalently, lower specifications for components.

We consider the alleviation of fatigue damage to be one of the primary uses of pitch regulation of wind turbines.

3 Review of control benefits

Consider a plant, i.e. a machine which responds dynamically to some external influence, Fig. 4*a*. The basic problem is to make the output follow the input. The solution is to employ a feedback loop. The output from the plant is measured and compared to the desired response with the error used to adjust the plant through a controller. This is the closed-loop system, Fig. 4*b*, as distinct from the system with the controller present but no feedback loop which is the open-loop system, Fig. 4*c*. It is the dynamic response of the closed-loop system (not the open-loop system) which determines system performance. As well as causing the output to follow the input the controller can achieve several things.

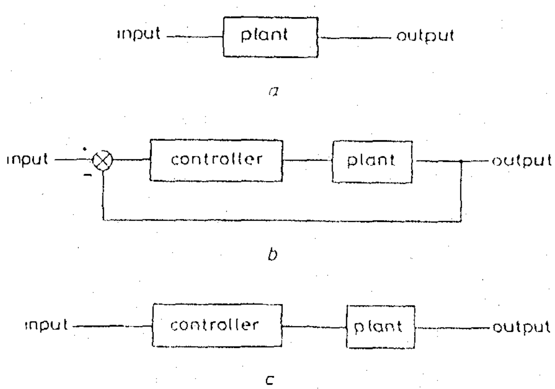

Fig. 4 *Controlled and uncontrolled systems*
a Uncontrolled system
b Closed-loop system
c Open-loop system

3.1 The controller determines the overall dynamics

Consider the following grossly simplified model of a wind turbine. The dynamics are represented by a second order spring, mass and damper system.

$$I\ddot{\phi} + B\dot{\phi} + K\phi = T_A \tag{3}$$

where I, B and K are the aggregate wind turbine inertia, damping and stiffness, $\ddot{\phi}$, $\dot{\phi}$ and ϕ are the rotor shaft acceleration, velocity and position. T_A is the rotor aerodynamic torque.

Control action is introduced by feedback from the system output, altering the input driving torque. A simple proportional plus integral control acting on shaft speed may be used as an illustration. The wind turbine model is modified to

$$I\ddot{\phi} + B\dot{\phi} + K\phi = T_A - T_f \tag{4}$$

where, the control action

$$T_F = k_1\phi + k_2\dot{\phi} \tag{5}$$

k_1 is the control integral gain on shaft speed and k_2 is the control proportional gain. Substituting eqn. 5 into eqn. 4 gives the amended dynamics

$$I\ddot{\phi} + (B + k_2)\dot{\phi} + (K + k_1)\phi = T_A \tag{6}$$

The damping factor of the system appears to have been modified to $(B + k_2)$ and the stiffness to $(K + k_1)$. Of course, they have not physically been altered, but the dynamics and all the forces experienced by the system behave as if the system had been altered as indicated.

If the control action of eqn. 5 can be introduced with no penalty, then the system performance could be altered to any desired form. Unfortunately, this is not possible. The first penalty is that the greater the alteration of the system then the harder the control action has to work. The second penalty arises since the measurement on which the control acts is inevitably corrupted by noise. The noise is fed into the system through the controller and adversely affects its performance. Again, the greater the alteration of the system the greater the penalty. When choosing a control design the tradeoff must be carefully assessed.

In general, the addition of damping is easier to achieve than the addition of stiffness. The use of feedback control can be used as an alternative to mechanical methods of increasing damping in the drive train.

3.2 The controller shapes the output spectrum

Consider the system in Fig. 5*a* where the dynamics are represented by $G(s)$, the transfer function of the system. If the system is linear and time-invariant then the dynamics are characterised by the response of the system to an impulse as indicated in Fig. 5*b*. $G(s)$ is the Laplace Transform of the impulse response function. To obtain spectral information about a system the frequency response function $K(\omega)$, which is 2π times the Fourier transform of the impulse response function, is required. For stable causal systems

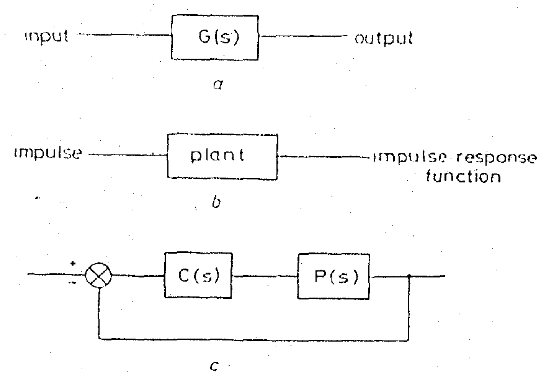

Fig. 5 *System transfer and response functions*
a Transfer function representation of open-loop system
b Impulse response of system
c Transfer function representation of closed-loop system

$$K(\omega) = G(j\omega) \tag{7}$$

Hence, for the system with transfer function $G(s)$

$$\text{spectrum of output} = |G(j\omega)|^2 \times \text{spectrum of input}$$

When the system is the closed-loop system, Fig. 5*c*, with $P(s)$ the transfer function of the plant and $C(s)$ the trans-

are characterised by its spectral content. The resulting torques and moments, to whi[illegible]e wind turbine structure and power train are su[illegible], are modified by the dynamics of the turbine and the control systems. The analysis of Madsen and Frandsen [6] is extended to identify the precise manner in which this occurs. The interaction is examined in some detail here.

The windspeed varies stochastically in both a temporal and spatial manner to form a three-dimensional wind field. It may be pictured as a tube throughout which the windspeed varies not only longitudinally but over the cross-section of the tube at any point. The longitudinal axis of the tube represents time and the wind turbine moves along the tube experiencing, at any one time, a cross-section of the tube. Thus, the wind turbine does not experience a single windspeed but a windspeed which varies over the disc swept by the rotor. The direction of the wind also varies in time and over the disc. Hence, the spectral representation of the windfield must be multidimensional to include the variations, both in magnitude and direction, of windspeed over the swept disc.

The windfield spectra, as seen at a point on the rotor, are shaped by the motion of the blades. First, the rotation of the rotor, as indicated in Fig. 11, changes the

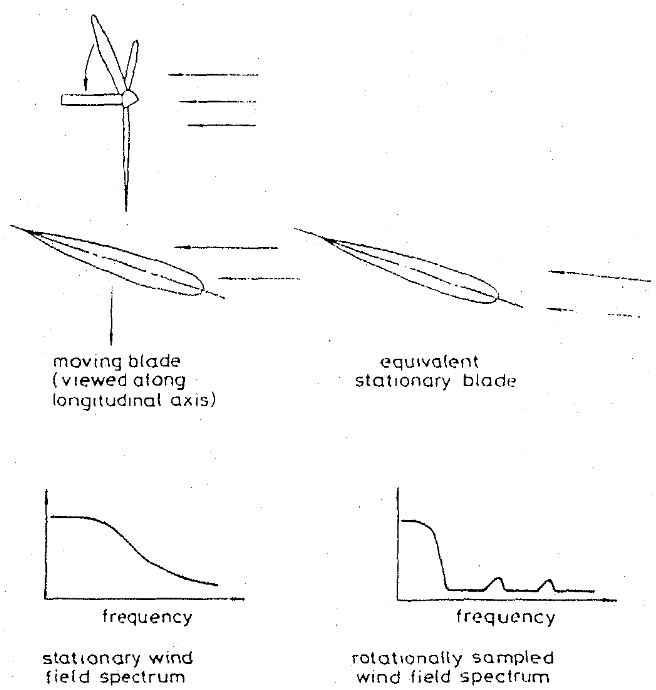

Fig. 11 *Effect of rotation of blades on wind field spectrum*

direction of the windspeed relative to the blades and accordingly modifies the spectra at all frequencies. In addition, it increases the high frequency parts of the spectra at multiples of Ω, the rotor angular velocity. This concentration in energy is caused by each blade in turn sweeping through variations in windspeed over the swept disc. The variation in windspeed includes tower shadow which is the reduction in windspeed in front of the tower, wind sheer which is the increase in windspeed with height as the boundary effects decrease and localised wind gusts. Secondly, the pitching of the blades about their longitudinal axis, as indicated in Fig. 12, again shapes the spectra by changing the relative windspeed. Thus in a fundamental way the control system, by changing pitch angle, influences all the wind induced forces and torques which drive the wind turbine dynamics.

In accordance with the response of the system to the fluctuating loa[illegible] the feedback control changes the blade pitch to cause change in the induced torques and moments. The effect of these changes in pitch can be

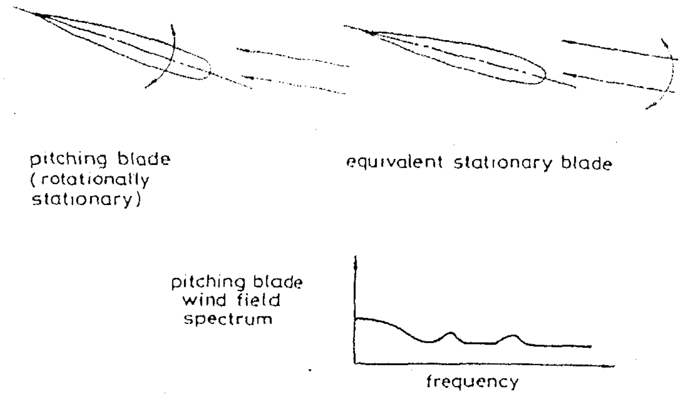

Fig. 12 *Effect of pitching blades on wind field spectrum*

interpreted as inducing equivalent changes in windspeed which leave the windfield spectra as experienced by a blade unaltered. Rather than changing pitch angle the influence of the control system may be depicted as in Fig. 13. P incorporates the aerodynamics which converts the

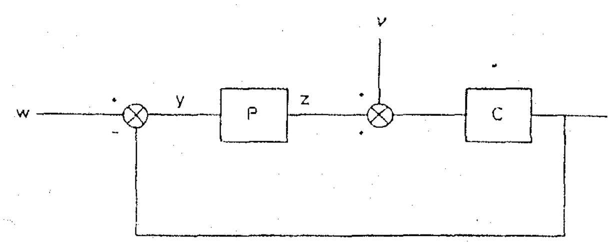

Fig. 13 *Modification of windspeed induced dynamics*

windspeed inputs into driving torques and forces, the structural dynamics, the power train dynamics and measurement transducer dynamics. C incorporates the control system dynamics, the pitch actuator dynamics and the dynamics required to convert changes in pitch angle to equivalent changes in windspeed. W are windspeed inputs, y are the equivalent windspeed inputs including the control action, z is the measured output of the turbine (usually power) and v is the measurement noise. Fig. 13 is an exact representation of the wind turbine. P and C are nonlinear operators which model the complete nonlinear dynamics of the system. Since it is the influence of the input y on the plant P that is of interest, an equivalent representation is as indicated in Fig. 14*a*.

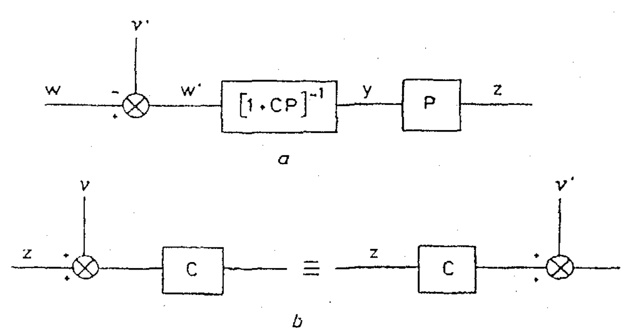

Fig. 14 *Equivalent representations*
a Equivalent representation of Fig. 13
b Equivalent measurement noise representations

noise and wind are assumed to be uncorrelated and from Fig. 14*a* the spectral density function for the turbulent

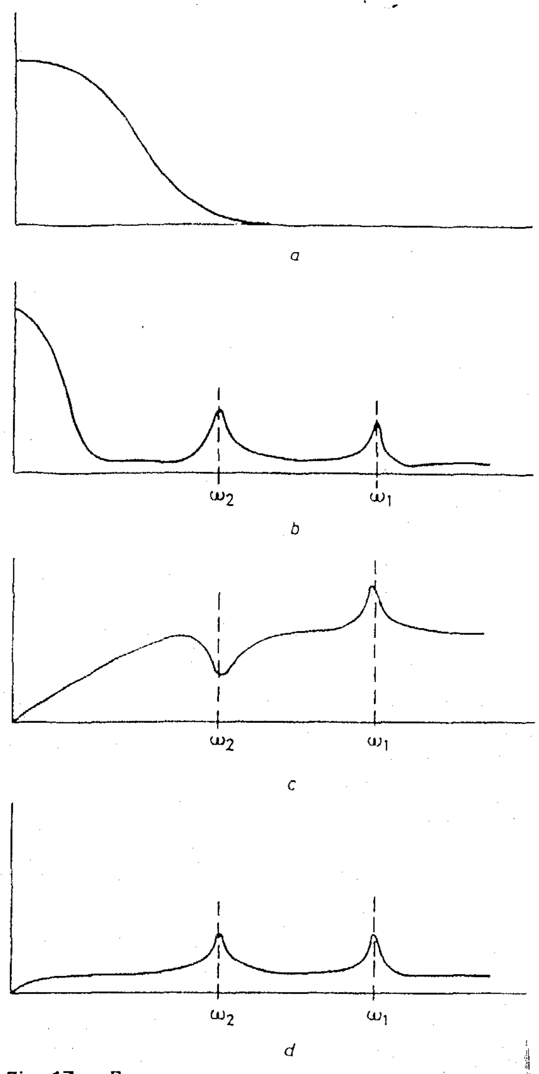

Fig. 17 *Frequency spectra*
a Von Karman spectrum
b Rotationally sampled spectrum
c $|1+CP|^{-2}$
d $|H|^2$

wind as experienced by the blades is amended to

$$S_{w'}(\omega) = S_w(\omega) + S_{v'}(\omega) \tag{9}$$

The wind spectrum experienced by the blades is not only modified by the rotational motion of the blades but is also modified by the axial motion of the blades, the bandwidth of which can easily include most of the significant frequency range of $S_{w'}(\omega)$. To obtain greater insight, the wind turbine system is linearised about some operating point. The operators $\boldsymbol{P}$, $\boldsymbol{C}$, $\boldsymbol{P}_1$, $\boldsymbol{P}_2$, $\boldsymbol{P}_3$, $\boldsymbol{P}_4$ and $\boldsymbol{C}_1$ become the transfer functions P, C, P_1, P_2, P_3, P_4 and C_1. The measurement noises are related by

$$v' = Cv \tag{10}$$

and their spectral density functions by

$$S_{v'}(\omega) = |C|^2 S_v(\omega) \tag{11}$$

The combined windspeed and measurement noise spectrum becomes

$$S_{w'}(\omega) = S_w(\omega) + |C|^2 S_v(\omega) \tag{12}$$

The limitation placed on the control by the presence of measurement noise as mentioned in Section 3 can be assessed from eqn. 11 or 12. The noise is usually assumed to be white noise when $S_v(\omega)$ becomes constant. The contribution of the noise to the input spectrum increases with $|C|$, and hence with the control gains.

By changing the pitch angle of the blades, the dynamics of the plant and controller modify the input to the wind turbine. From the previous discussion, it can be interpreted as being due to a turbulent wind, and from Fig. 18*b* the effective spectral density function is

$$S_E(\omega) = \frac{1}{|1+CP|^2} S_{w'}(\omega) \tag{13}$$

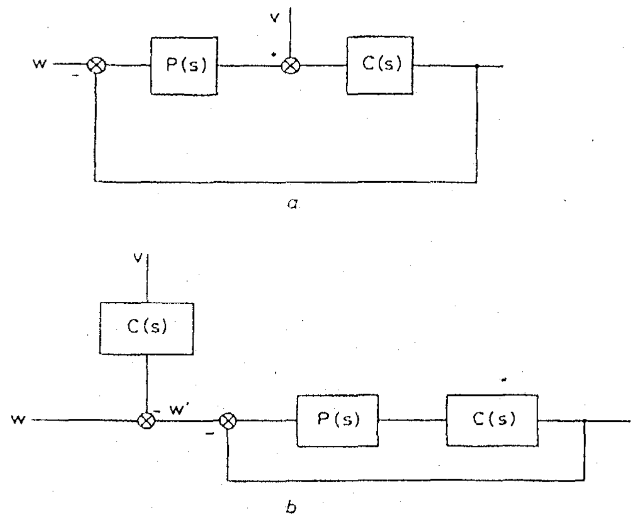

Fig. 18 *Dynamics models*
a Linearised model of wind turbine dynamics
b Equivalent representation of dynamics

In Madsen and Frandsen [6] it was essentially assumed that

$$CP = (\alpha f_0)/(j\omega) \tag{14}$$

i.e. the power train was assumed to have no dynamics and the control was simple integral action.

7 Influence of control systems on tower and blades

To estimate the loads on the blades and tower, the structural dynamics must be driven by a wind input modified by the operator $[1 + CP]^{-1}$. However, to assess the influence of the control action on a particular blade or combined blade and tower mode of the structural dynamics, only the frequency response function H, coupling the input to that mode need be known. A possible shaping function, $|1 + CP|^{-2}$, is shown in Fig. 17*c* and $|H(\omega)|^2$ in Fig. 17*d*. A comparative estimate of the structural loads can be determined directly from the effective windspeed spectrum. The spectral density function, $S_S(\omega)$ for the resulting excitation of the mode is

$$S_s(\omega) = \frac{|H|^2}{|1+CP|^2} S_{w'}(\omega) \tag{15}$$

The contributions of all the significant structural modes need to be included.

control design purposes has the following structure

$$
\begin{array}{ll}
\text{Structural loads} & J = \displaystyle\int_{-\infty}^{\infty} \{a_1^2 |H_1|^2 S_E(\omega) \\
\text{Gearbox loads} & + a_2^2 S_{GB}(\omega) \\
\text{Generator loads} & + a_3^2 S_G(\omega) \\
\text{Transverse tower loads} & a_4^2 |H_2|^2 S_{GB}(\omega) \\
\text{Power smoothness} & + a_5^2 S_P(\omega) \\
\text{Control cost} & + a_6^2 |H_3|^2 S_C(\omega)\} \, d\omega
\end{array}
\qquad (22)
$$

The control system is designed to minimise, in some sense, the cost function, J. It is simply a weighted average of the power associated with each of the indicators of performance previously discussed.

The various spectra in the cost function (22) are

$$
\begin{aligned}
S_{GB}(\omega) &= |P_1|^2 S_E(\omega) \\
S_G(\omega) &= |P_2 P_1|^2 S_E(\omega) \\
S_P(\omega) &= |P_4 P_1|^2 S_E(\omega) \\
S_C(\omega) &= |C_1|^2 |1 + CP|^{-2} (|P_1 P_4|^2 S_w(\omega) + S_v(\omega)) \qquad (23)
\end{aligned}
$$

The relative importance of each of the terms reflected in the value of the scale factors, a_i, is strongly dependent on the turbine configuration and will inevitably involve tradeoffs. Although J seems complex many of the terms will be negligible and may be left out when used to assess a particular wind turbine. Moreover, a complex cost function need not necessarily give rise to a complex control system design, but allows a more thorough evaluation.

10 Control and structural fatigue

Although the influence of the control system on the structural loads has been discussed, the relevance for structural fatigue remains to be clarified. The structural loads can be considered to be composed of three components. The first contribution to the total is the mean loads over the rotor disc which would arise if the blades are controlled perfectly and the pitch angle is appropriately set for the mean windspeed experienced by the wind turbine at any given time, i.e. the design loads. The second is the mean loads over the rotor disc which arise from the control being imperfect and the pitch angle not being appropriately set, i.e. the off design loads. The third is the loads due to the variation of the windspeed over the rotor disc which occur at multiples of the rotor angular velocity Ω, i.e. the cyclic loads.

In the main above rated windspeed, the design loads are less for a pitch regulated than for a stall regulated machine but the cyclic loads are larger. Of course, the off design loads are not applicable to a stall regulated wind turbine. However, it is not our purpose to compare pitch regulation to stall regulation.

The fatigue damage is assessed by counting the number of occurrences of cycles with each possible amplitude in the total loads. The bulk of the damage is caused by the cycles with greatest amplitude which occur at low frequency [2, 3]. It is the superposition of the three components of the structural loads which generate these low frequency cycles. Even though it is not possible to remove the low frequency cycles, reducing the higher frequency components of the loads reduces the fatigue damage caused by them by reducing their amplitude.

The control system affects the structural fatigue by determining th[illegible]nt of the off-design loads. One of the objectives of the control system should be to reduce these. In addition, if the control system of a constant speed wind turbine (Section 11), performs poorly in regulating drive train loads, particularly as the mean windspeed increases, then the power rating of the wind turbine may need to be reduced with rising windspeed. A consequence is an increase in fatigue damage since the amplitude of the low frequency cycles of the structural design loads increases. For a variable speed variable pitch wind turbine (Section 12), the pitch angle of the blades is controlled in response to a measurement of rotor speed. When the machine is subject to a change in windspeed, the pitch angle is only adjusted after the rotor speed has responded to the induced changes in the rotor torque. Because of the large rotor inertia the pitch regulation is slow and the wind turbine experiences large off design loads.

The control system also affects the structural fatigue by indirectly influencing the extent of part of the cyclic loads. Since all blades are assumed to act in unison, only those cyclic loads which enter the drive train and the cyclic loads which are correlated to them are affected. Usually, the most important of these cyclic loads are those which have frequency $n\Omega$ where n is the number of blades. They occur at too high a frequency to be directly controlled but at these frequencies the control system acts to enhance disturbances rather than to reduce them. Hence, the controller may increase substantially the cyclic loads of frequency n. For example, in respect to the tower shadow cyclic load on a two bladed wind turbine, the blades may be adjusted 180° out of phase to the response required to smooth the tower shadow cyclic load.

11 Constant speed wind turbines

A constant speed wind turbine is a simple configuration with the generator connected to the grid and directly driven by the drive train.

There is an extensive literature on the control of constant speed wind turbines with about 100 publications [12]. However, no treatment of the problem is entirely satisfactory. Frequently, there is no clear statement of the control objectives but the most common, often unstated, are

(*a*) power limiting
(*b*) power smoothing
(*c*) response to isolated gusts or ramps.

The treatment of the dynamics and the stochastic nature of the windspeed is also sometimes inadequate. The most thorough investigation to date is Mattsson [13].

The constant speed wind turbine configuration is characterised by stiff power train dynamics. The electrical generator is locked to the grid, thereby permitting only small deviations of the rotor shaft speed from the nominal value. The system is very responsive to wind induced load disturbances.

A typical wind turbine with appropriate rating for a given site spends about 25% of the time in each of the following modes [2]:

(i) shutdown as the windspeed is too low
(ii) generating below rated power
(iii) operating near rated windspeed, i.e. at the knee of the power curve
(iv) operating above rated windspeed.

the system (by inclusion of feedback of slip measurement) improves performance [16, 17]. The reason is that the power train dynamics are characterisable as two modes. The first mode at low frequency is often near the bandwidth of the control system and is lightly damped to avoid the unnecessary dissipation of energy. Unfortunately, PI control is unable to add damping. Consider the control action

$$k_1 + \frac{k_2}{s} = k\left(\frac{s + a}{a}\right) \tag{26}$$

Fig. 22 shows part of the root locus for the dynamics of a typical wind turbine. The complex conjugate pair of poles are the first mode of the drive-train. When feedback is employed, k causes this pair of poles to track towards the imaginary axis and so reduces the degree of damping.

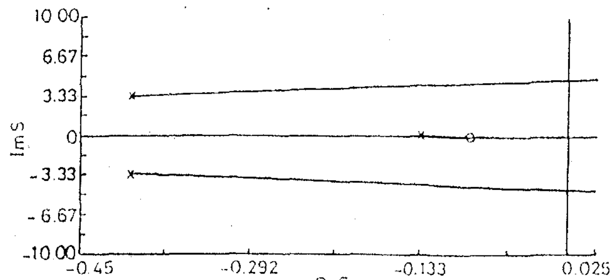

Fig. 22 *Part of root locus of open-loop system*

The Bode plot for $(s + a)/s$, Fig. 23 (for a nominally 10 rev/s) illustrates that it reduces the open-loop phase margin and so, also, must reduce damping. The obvious remedy of derivative action is not applicable because of the stochastic nature of the windspeed turbulence.

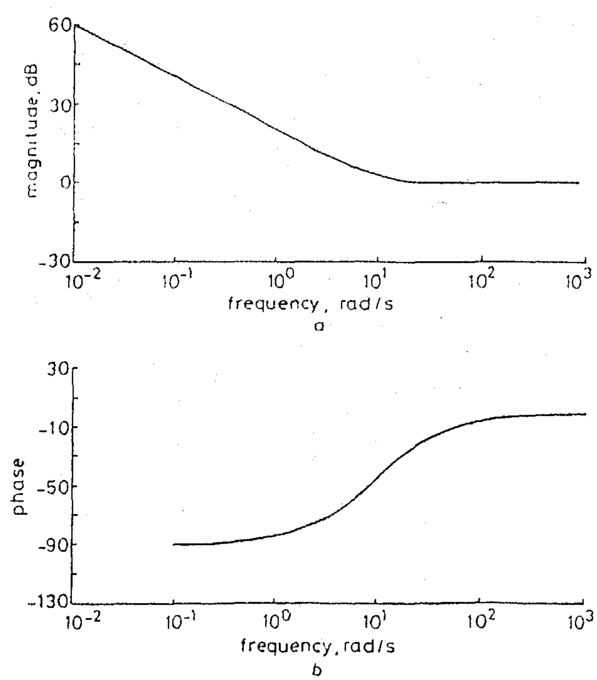

Fig. 23 *Bode Plot of $(s + a)/s$ with $a = 10$ rev/s*
PI compensator $k = (s + 10/s)$

One further goal the control system should attempt to realise is to maximise the energy capture of the wind turbine, particularly when operating near to the rated windspeed. The aims of the control system [1] are summarised as follows:

(*a*) Alleviate transient loads throughout the wind turbine to relieve stresses.

(*b*) Regulate and smooth the power generated.

(*c*) Shape the dynamics to satisfy the usual performance criterion, i.e. impart satisfactory stability margins and steady state errors.

(*d*) Maximise energy capture.

12 Variable speed wind turbines

In variable speed wind turbines the generator does not directly couple the grid to the drive train. Instead the rotor is permitted to rotate at any speed by the power generation unit which might typically be a generator-rectifier-inverter combination.

The ability to operate at varying rotor speed, effectively adds compliance to the power train dynamics of the wind turbine. Hence, although all the aspects investigated in Sections 7 and 8 are still relevant, the weighting given to the goals of alleviating stress on the power train need not be so great. However, it must still be evaluated. As the shaft speed varies the frequency of the peaks of $S_w(\omega)$ vary as does the frequency of the structural modes, although the extent of the variation for the latter is relatively small [2, 5]. It may be assumed the rate of change of the mean rotor speed is slow compared to the rapid fluctuations in the windspeed and loads. The variable speed wind turbine can, thus, be analysed quasistatically in the manner of the constant speed wind turbine. Because of this movement in the spectral peaks the requirement on the structural dynamic loads may be more stringent.

For the variable speed wind turbine there may be more than one control action. When the power generation is by an AC-DC-AC link there are three, namely

(i) an AVR (automatic voltage regulator) on the generator output voltage

(ii) control of the power electronics links to the grid

(iii) variable blade pitch.

In addition to power measurement, a measurement of shaft speed may also be made. Used in conjunction (i) and (ii) control the electrical power generated and therefore the generator reaction torque which obviously influences the rotor speed. Control without pitch action through the generator reaction torque can be analysed in a similar manner to pitch regulation, but without the shaping of the windspeed spectral density function by $|1 + CP|^{-2}$. Whether satisfactory control can be attained in this manner alone, e.g. by stalling the rotor above rated windspeed, needs to be investigated. Alternatively active pitch control is used in conjunction with generator reaction torque. In the latter case the design of the control system is a genuine two input two output control problem with significant interaction between the two control actions [18].

There are a variety of different operating strategies for variable speed wind turbines and each could be evaluated separately. The turbine is caused to track a predefined torque-speed trajectory and an additional goal of the control system is to track this trajectory as closely as possible [19]. A typical strategy is described below.

Below rated wind speed the operation of the turbine is regulated by varying the generator winding voltage or the inverter firing angle. In essence the load on the generator is adjusted and so is the reaction torque the gener-

their associated noise problems, no component of the power train should act as a low pass filter in the frequency range of the control system, i.e. the bandwidth for each component must be greater than the characteristic frequency. Consider the power train, Fig. 25. None of the components should prevent information from passing down the power train to the output measurement. If a component does, relevant information becomes unavailable to the control system which is rendered ineffective for part of its frequency range. An additional measurement before the restriction is necessary to recover the lost information.

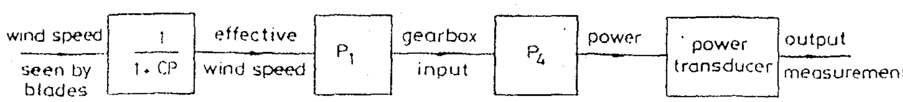

Fig. 25 *Flow of information along wind turbine power train*

15 Implications of control for cost of power generation

The control system has implications for the cost of power generation by wind turbines since it reduces the load fluctuations and stress to which the machine is subject. The specification of components can be set closer to the nominal rating. The control system can also improve the rate of energy capture. Both of these factors are related to the cost of power generation. Only a thorough investigation of the control design problem can clarify the tradeoff decisions contributing to a minimum cost, long life system.

16 Summary and conclusions

Variable pitch control on wind turbines was introduced for the following reasons. Turbines must be capable of being started and run up to speed in a safe and controlled manner; stopping must be similarly controlled. In emergency conditions overspeed protection must be provided and industrial practice has tended not to favour a reliance solely on mechanical brakes. The general opinion is that some aerodynamic assistance is preferred for these operations. The power of the wind increases sharply with windspeed. At a predetermined windspeed the power input to the turbine will have reached the limit for safe operation. To prevent overload as the windspeed rises above rated, the turbine must be regulated to spill the excess power in the wind.

Rapid windspeed changes produce variation in loads which cannot be completely eliminated. Reducing the magnitude of these variations is desirable as it allows the turbine to be operated closer to its design limits without fear of electrical or stress overloads; an increase in power production or a reduction of component ratings are thus possible. 'Smooth' output power also has a traditional appeal to the electricity supply industry as it has no experience of such rapidly fluctuating power sources. The more refined commercial turbines strive to obtain 'good power quality'.

Improvement in power quality can be achieved by using a control system which monitors the turbine and alters the pitch angle of the blades accordingly. An alternative is to design a fixed pitch rotor with blades that stall at the rated windspeed. A stalling rotor is self-regulating providing power regulation and good power quality without a control system. Start up, shut down and overspeed protection of such a rotor, requires further consideration. Stall regulation is still at the development stage and will not immediately supersede pitch regulation, particularly for large machines.

Power quality, alone, is too blunt a criterion on which to assess the design of the controller for variable pitch regulation. There is an extensive range of strategies which can be adopted without significant loss of power quality. The dynamics of the controller interact with the dynamics of the structure and so have implications for the fatigue life of the turbine. Similarly, the dynamics of the controller interact with the dynamics of the drive train and have implications for the fatigue life of the drive train components. The choice of control strategy moderates or accentuates the torques and moments to which the components of the wind turbine are subject. If the torques and moments are moderated then, of course, the power quality improves, but to improve the power quality alone will not by itself moderate the torques and moments. Good control must aim to moderate them.

The relative importance of each of the factors involved in the assessment of the control design is strongly dependent on the turbine configuration and inevitably will involve tradeoffs. For variable speed machines some requirements can be relaxed because of the increased compliance in the drive train as compared to the constant speed case. But others become more stringent since the shaft speed varies and the turbine is caused to track a predefined torque-speed trajectory.

To date wind turbine control has been judged in terms of power quality or in terms of the response of the wind turbine to simple wind profiles such as an isolated gust or ramp in windspeed. These are not adequate criteria on their own. 'Good control' should aim to realise the following objectives:

(*a*) Relieve stress and reduce fatigue on the wind turbine by smoothing the torques and moments throughout the systems.

(*b*) Maximise energy capture of the wind turbine.

(*c*) Regulate and smooth the power generated.

(*d*) Shape the dynamics of the complete power train to the usual performance criterion, i.e. impart satisfactory damping and steady state behaviour.

Active pitch control modifies the spectral density function of the windspeed the wind turbine effectively experiences. This effective spectral density function generates the fluctuating loads to which the wind turbine is subject. One approach to wind turbine design is to overengineer the system to the extent that the structural and power train dynamics decouple and the components are specified to be capable of absorbing all the fluctuating loads. An alternative is to reduce the over-engineering to a minimum by regulating the response of the wind turbine to the fluctuating loads. The historic trend is to the latter as turbines become lighter, more flexible and hence more cost effective [21]. To investigate and assess any aspect of performance of such wind turbines requires the dynamics to be subject to the correct input. That requires the shaping by the action of the controller to be incorporated and is dependent on the quality of the control. Likewise, that the action of the control system shapes the input in